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Key Points:
- The equatorial thermocline should be computed as the maximum vertical thermal gradient. The 20 °C isotherm shows different depth and slope
- The 20 °C isotherm depth is too dependent on model sea surface temperature bias in the eastern Pacific
- Thermocline depth is more sensitive to equatorial zonal wind stress than a representative isotherm

Supporting Information:
- Supporting Information S1
- Figure SM1
- Figure SM2
- Figure SM3
- Figure SM4

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Revisiting the CMIP5 Thermocline in the Equatorial Pacific and Atlantic Oceans

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Abstract The thermocline is defined as the ocean layer for which the vertical thermal gradient is maximum. In the equatorial ocean, observations led to the use of the 20 °C isotherm depth (z20) as an estimate of the thermocline. This study compares z20 against the physical thermocline in the equatorial Atlantic and Pacific Oceans, using Simple Ocean Data Assimilation reanalysis and fifth phase of the Coupled Model Intercomparison Project preindustrial control simulations. Our results show that z20 is systematically deeper and flatter than the thermocline and does not respond correctly to surface wind stress variations. It is also shown that the annual cycle of z20 is much weaker than that of the physical thermocline. This happens in both equatorial basins and indicates that z20 does not react to the same mechanisms as the thermocline. This could have important consequences in the assessment of air-sea coupling in current general circulation models and bias reduction strategies.

Plain Language Summary The thermocline is the layer that separates the upper ocean, which interacts with the atmosphere, and the deep ocean. This layer has been identified, in the equatorial Pacific and Atlantic Oceans, with that where the water temperature reaches 20 °C. The present work makes the case for estimating its depth using the physical definition of the thermocline instead of the 20° isotherm. We present evidence of problems entailed by using the estimate, especially when working with global climate models. Also, we present the advantages of using the physical definition, such as a more realistic explanation of wind-ocean interactions. Model-by-model study shows that users of particular coupled models should be especially cautious due to errors in the 20° isotherm method being more important in some models than others.

1. Introduction

The layer of the ocean in which the vertical temperature gradient is maximum is known as the thermocline (Sverdrup et al., 1942). This term is frequently used to refer to a discontinuity layer (Sverdrup et al., 1942). In tropical regions, in absence of strong vertical salinity gradients, the thermocline constitutes the lower boundary of the mixed layer, isolating the deep ocean from the subsurface layer (Breugem et al., 2008). Most air-sea interaction processes take place above the thermocline, so correctly assessing its position is fundamental for understanding ocean–atmosphere interaction processes (Li & Xie, 2012). A shallower thermocline will be more easily influenced by wind and surface temperature changes, while a deeper one will be less responsive to these variations.

Historically, locating the thermocline in the ocean has been a difficult task due to the lack of specialized equipment (Sverdrup et al., 1942). This fact led to an array of techniques (Fiedler, 2010), of which the depth of different representative isotherms as an estimate for the depth of the thermocline was the most usual. The chosen isotherm depends on the latitude and the ocean studied in each case (Kessler, 1990; Yang & Wang, 2009). There are other methods which present advantages and disadvantages depending on the region studied (Fiedler, 2010). However, the representative isotherm is almost unanimously used in model studies (e.g., Cai et al., 2004; Deppenmeier et al., 2016; Li et al., 2015, 2016; Song et al., 2014). Our study focuses on the equatorial Pacific and Atlantic Oceans, two key regions regarding air-sea interactions. The equatorial Pacific is where the main mode of interannual climate variability, the El Niño-Southern Oscillation, occurs. The Atlantic basin hosts its own El Niño phenomenon (Zebiak, 1993). The isotherm usually selected to represent the thermocline in equatorial oceans is 20 °C (Lengaigne et al., 2012; Li & Xie, 2014; Lübbecke & McPhaden, 2017; Martín-Rey et al., 2014; Xiang et al., 2017), although some studies have used the depth of the 22 °C isotherm (Deppenmeier et al., 2016) or 23 °C isotherm (Cabos et al., 2017) in the tropical Atlantic. With the development and general adoption of general circulation models, the depth of a representative isotherm (generally the 20 °C one, hereafter, z20) as estimate of the thermocline depth was kept to compare model and observations, given the relatively poor vertical resolution of ocean models (Yang & Wang, 2009).

The fifth phase of the Coupled Model Intercomparison Project (CMIP5) provides an advantageous platform to intercompare state-of-the-art general circulation models. It is generally accepted that these models suffer from important biases in the tropical Pacific (Wang et al., 2014), producing an excessively strong and narrow cold tongue and a double intertropical convergence zone (Bellucci et al., 2010; Li & Xie, 2014; Oueslati & Bellon, 2015; Xiang et al., 2017). Many works have tried to ascertain the origin of these errors and most trace them to a deficient dynamic feedback mechanism between the atmosphere and the ocean in coupled models (Bjerknes, 1969; Li et al., 2015, 2016; Li & Xie, 2014; Richter, 2015). Regarding the tropical Atlantic Ocean, general circulation models are also afflicted by serious biases (Richter, 2015; Zuidema et al., 2016) that affect both sea surface temperature (SST) variability (Richter et al., 2014) and basin feedback processes (Ding et al., 2015; Nnamchi et al., 2015; Voldoire et al., 2014). Of particular interest to our study is the relationship between a too weak wind and a badly represented thermocline (Richter et al., 2014). This affects the mentioned feedback processes, mainly the formation and maintaining of the equatorial cold tongue (Richter et al., 2014; Voldoire et al., 2014), which is one of the main features of the equatorial Atlantic atmosphere–ocean interaction.

Yang and Wang (2009) explored the impact of using z20 as an estimate for the depth of the thermocline on the study of mean climate shifts. They concluded that using z20 in a warming ocean could lead to relevant errors in the assessment of trends of the thermocline depth. Despite these findings, the climate community has continued using z20 as the depth of the thermocline for observations and coupled models alike (Li et al., 2015, 2016; Richter, 2015).

This paper compares the widely used z20 estimate with the depth of the maximum temperature gradient, as proposed by Yang and Wang (2009). It explores the impact of using the physical definition or the z20 estimate, assessing the behavior of the thermocline in the equatorial band and identifying the physical processes involved in atmosphere–ocean coupling. To this aim, an ensemble of 24 CMIP5 models is used, and intermodel spread and behavior are analyzed, following the methodology applied in previous works (e.g., Deppenmeier et al., 2016; Flato et al., 2013; Li et al., 2015; Wang et al., 2014).

2. Data and Methods

This study uses monthly mean ocean potential temperature data (1979–2010) from the Simple Ocean Data Assimilation (SODA) reanalysis v2 (Carton et al., 2005); SST data (1854–2014) from ERSST v3b (Smith et al., 2008); and ocean potential temperature, wind stress, and SST data from 24 CMIP5 models (Taylor et al., 2012). The models analyzed are listed in Table S1 in the supporting information. The horizontal resolution of the SODA reanalysis is 1 × 1° in the area of interest, and the CMIP5 models have been interpolated to that grid. The areas of study are the tropical Pacific (30°S to 30°N and 80°W to 150°E) and the tropical Atlantic (30°S to 30°N and 30°W to 10°E). Two regions have been selected within the Pacific: central Pacific (160°E to 140°W) and eastern Pacific (110°W to 80°W) and one in the Atlantic (30°W to 10°W). We use monthly data for each model. Calculation of z20 and thermocline depth are based on them, and annual climatologies are computed from these data. CMIP5 preindustrial control simulation provides very long time series without the influence of varying radiative forcing. Two-hundred years has been chosen from each model (except for the MIROC-ESM-CHEM model, for which only 100 years was available), as a compromise between representativeness of the whole run and giving each model the same weight in the ensemble means.

To evaluate relationships among variables, intermodel correlations have been performed using the 24 climatological values (one per model) as "time" series. Positive correlations mean that models with high values for a variable show high values in the other variable as well. The use of intermodel correlations follows the methodology used in other intercomparison exercises done with CMIP5 models (Deppenmeier et al., 2016; Flato et al., 2013; Li et al., 2015; Wang et al., 2014). Nevertheless, monthly climatologies have also been used in order to study the annual cycle of each model and make intramodel comparison between z20 and thermocline depth. Significance of all correlations computed in this paper is established attending to the 95% confidence level using a two-tailed Student's *t* test.

Both z20 and the maximum vertical gradient are estimated from the 3-D ocean potential temperature. In order to be faithful to the vertical structure of the data, every operation is made on the original vertical layers for each model and the reanalysis, so no interpolation is performed in that direction. For z20, the layer with the temperature closest to 20 °C among those higher than 20 is selected (z20+), as well as the layer with the temperature closest to 20 °C among those cooler than 20 (z20−). Then, z20 is estimated by linear interpolation between those two layers. Vertical temperature inversions, which could lead to the existence of two 20 °C isotherms in the ocean, are usually related to seasonal variability (Mignot et al., 2012). A test has been performed for each grid point in order to check whether there was any thermal inversion in the first 500 m, and it was found that these situations were very infrequent, happening in less than 0.5% of the cases. Therefore, the points in which this occurred were taken out of the computations.

Regarding the depth of the maximum vertical temperature gradient, for each two consecutive layers (Z_{lev1} and Z_{lev2}), the gradient is computed as $\frac{-(Tlev2-Tlev1)}{Zlev2-Zlev1}$ (T_{lev1} and T_{lev2} being the temperature of the layers characterized by Z_{lev1} and Z_{lev2}, respectively) and the maximum value is obtained. Since this maximum gradient characterizes a depth between two layers, we assign the depth of the thermocline to the middle point between those two layers. By design, the method cannot be more precise than half the width of the level. This means a precision of 5 m for most models in the layers going from the surface to 200 m deep, which encompass almost all of the results found in our study.

The two methods are applied to all the points between 5°S and 5°N, and then averaged in latitude to find the mean equatorial depth as a function of longitude. Hereafter, we will refer to the depth of the maximum vertical temperature gradient as the depth of the thermocline.

3. Results

3.1. Equatorial Pacific Thermocline

The physical thermocline (given by the maximum gradient) tends to be shallower than z20, both for SODA and for CMIP5 models in the Pacific basin, especially in the east and west (Figure 1). The difference between both methods is bigger for the model mean than for the reanalysis (Figure 1a).

Although the absolute differences between z20 and the depth of the thermocline are similar in the eastern and western equatorial Pacific, the relative differences are higher for the east (6.1% and 17% for SODA and CMIP5, respectively) than for west (3.5% and 6% for SODA and CMIP5, respectively). Such differences increase when the seasonal cycle is taken into account: for the eastern region, the relative difference between both measurements reaches 26% in CMIP5 ensemble mean for the March-April-May period.

The annual cycle of the thermocline depth in CMIP5 models is similar to the observed one (Figures 1b and 1c). This, however, is not the case for z20 in the eastern Pacific (Figure 1c). This feature can be explained by the deeper location of z20 and, thus, less interaction with the atmosphere and radiative forcings. Differences between both methods in particular models are greater than that of the ensemble mean (Figures SM1 and SM2).

We further focus on the relationship between the SST and the depth of the thermocline in order to better understand what drives the differences in both methods for the ensemble of models. SSTs characterize the interface between ocean and atmosphere, providing an estimate of the heat content of the ocean. Since biases in SST can either have thermodynamical or dynamical origins (Li et al., 2016), understanding the thermocline's influence on SST bias is crucial.

In the eastern Pacific the local correlation between z20 and SST is statistically significant, while there is no significant correlation between the thermocline depth and SST (Figure 2a). This is clearer in Figures 2c and 2e, where the scatterplots of SST biases versus the thermocline depth and z20 in the eastern Pacific are shown. The positive correlation found between z20 and SST biases in the eastern part of the basin can be understood as a local response due to the shallowness of this isotherm in this region: the depth of a given isotherm depends on the number of isotherms above it, and so a model with a warmer SST will have a deeper 20 °C isotherm. Moreover, the correlation between z20 and depth of the thermocline in this region decreases and is nonsignificant, reinforcing that z20 is not a good estimate of the thermocline depth for the eastern Pacific. These results suggest that the use of z20 to estimate the thermocline depth should be avoided in

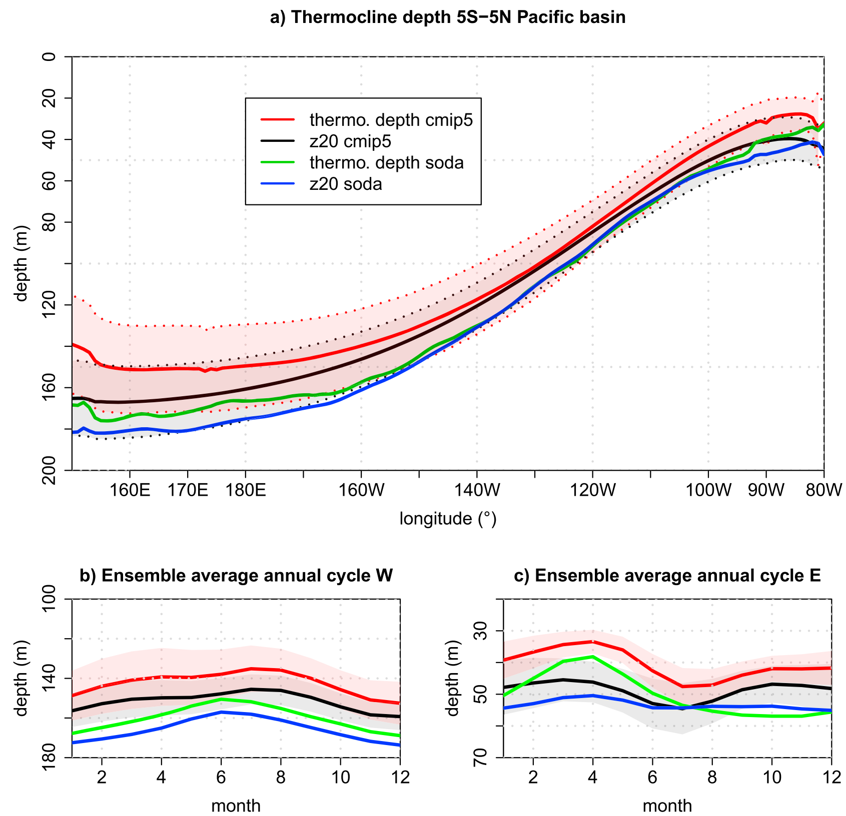

Figure 1. (a) Averaged (5°S–5°N) mean depth for the Pacific of SODA thermocline (green), CMIP5-ensemble thermocline (red), SODA z20 (blue), and CMIP5-ensemble z20 (black). Colored area shows model spread (±1 SD) for CMIP5 members. (b) Averaged (5°S–5°N) monthly mean depth for the western Pacific of SODA thermocline (green), CMIP5-ensemble thermocline (red), SODA z20 (blue), and CMIP5-ensemble z20 (black). Colored area shows interannual variability for CMIP5 members. (c) Same as in (b) but for eastern basin.

the eastern equatorial Pacific and that conclusions drawn when using it should be revised (e.g., Li et al., 2016), because our results suggest that there is no link between the SST biases and those of the thermocline depth in this region.

Conversely, both estimates show very strong and significant correlation between them over the central-west equatorial Pacific (Figure 2a). Both also show a local negative correlation with SST, although it is barely significant for z20 (Figures 2a, 2b, and 2d). In this region, where mean model biases are cold (Wang et al., 2014), our results suggest that cooler models have deeper thermoclines. In order to further understand this relationship, we analyze how the zonal wind stress interacts with the depth of the maximum gradient and z20. This is achieved by assessing the local effects of zonal wind (Figure 3a) and the remote effects of both zonal and meridional winds (Figures 3b and 3c). Local correlation between the equatorial zonal wind stress and the thermocline depth (Figure 3a, red line) suggests that models with stronger easterly winds at the equator have deeper thermoclines. Conversely, such link is underestimated when using z20 (Figure 3a, blue line). In turn, regarding SSTs in the central part of the basin, a positive correlation with the zonal wind stress is found (Figure 3a, black line), suggesting that colder SSTs are connected to stronger easterly winds. Three different mechanisms could be involved in the SST-wind-thermocline relationship. First, stronger easterlies would pile the warm water to the west deepening the thermocline there, but producing a local cooling of the SSTs due to thermodynamical processes. Second, such cooling of the ocean's surface would increase its density, which could, in turn, lead to increased vertical instability and mixing and a further deepening of the thermocline. This mechanism could be helped by local stirring due to the kinetic energy transferred by local wind stress to the underlying subsurface of the ocean. Third, and focusing on Figures 3b and 3c, off-equatorial winds could also influence the thermocline, through anomalous Sverdrup latitudinal transport.

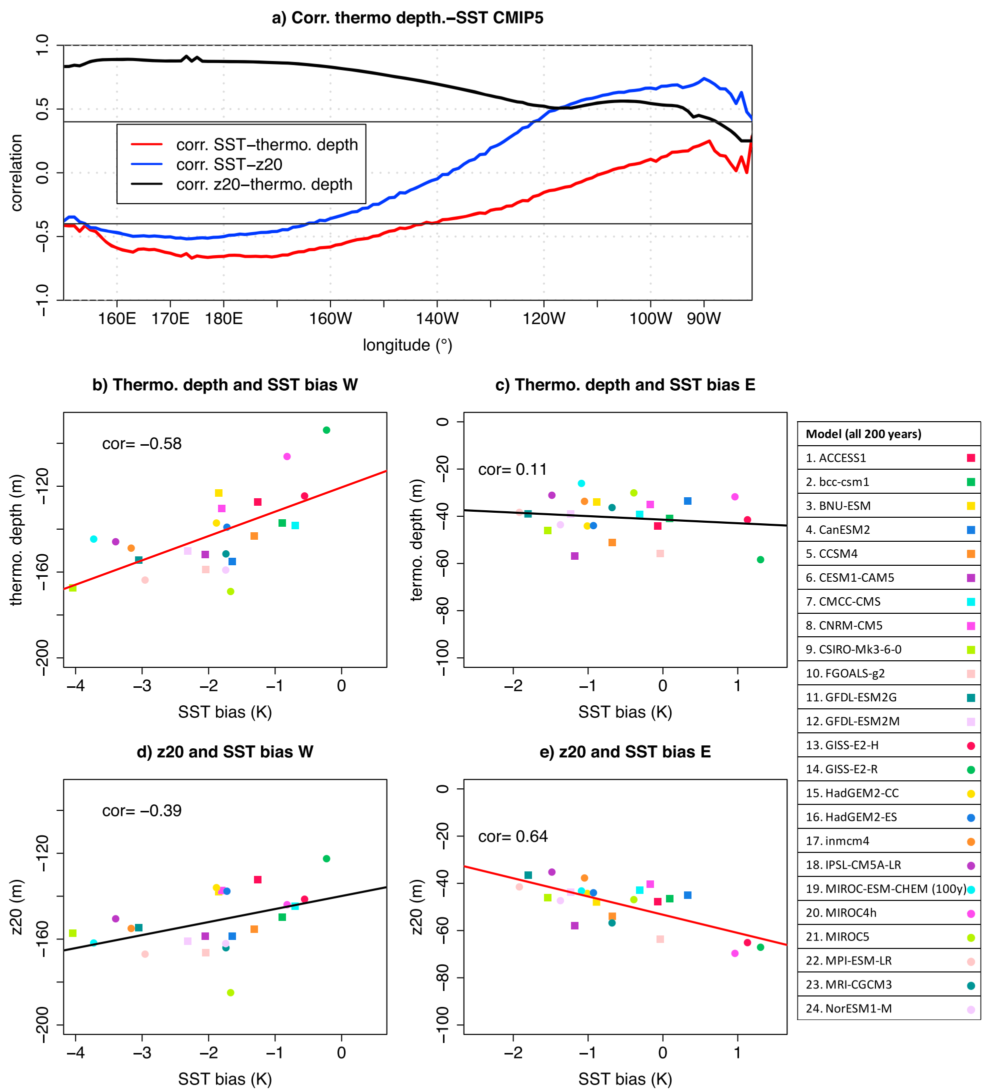

Figure 2. (a) Intermodel correlation between thermocline depth and SST (red) and z20 and SST (blue) for CMIP5 models in the equatorial (5°S–5°N) Pacific. Black line shows z20-thermocline depth correlation. Black horizontal lines show values over/under which correlation is significant. (b) Scatterplot and linear fit between SST bias and thermocline depth in the equatorial western Pacific (averaged between 160°E and 140°W) for CMIP5 models. (c) Same as in Figure 2b but for eastern Pacific. (d) Scatterplot and linear fit between SST bias and z20 in the equatorial western Pacific (averaged between 160°E and 140°W) for CMIP5 models. (e) Same as in Figure 2d but for eastern Pacific.

Sverdrup mass transport *V* is given by

$$V = \hat{k} \cdot \frac{\nabla \times \tau}{\beta} \tag{1}$$

where $\hat{k} \cdot \nabla \times \tau$ is the horizontal wind stress curl and ß is the rate of change with latitude of the Coriolis parameter.

The increase of easterlies from the equator poleward up to 10–15° drives a Sverdrup mass transport out of the equator. However, the anomalous zonal wind stress pattern in Figure 3b shows maximum easterlies at the equator and weaker anomalies poleward. The associated equatorward anomalous Sverdrup is, therefore, consistent with a deeper thermocline. This suggests that models showing a weaker (stronger) latitudinal gradient of zonal wind tend to show a deeper (shallower) thermocline. The whole mechanism is visible for the thermocline depth (Figure 3b), while for z20 only the remote effects are apparent and not the zonal equatorial piling of water (lack of gray inside index box).

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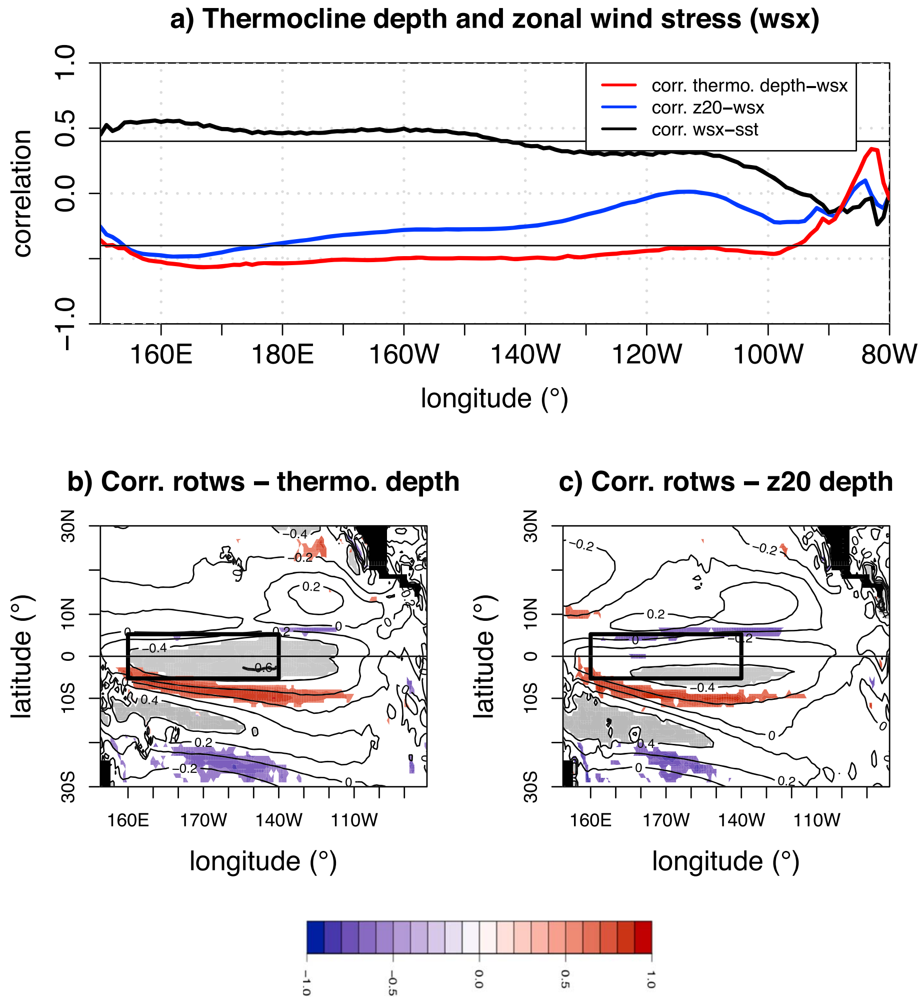

Figure 3. (a) Intermodel local thermocline depth-zonal wind stress correlation (red) and z20-zonal wind stress (blue) for CMIP5 models in the equatorial (5°S–5°N) Pacific. Black line shows correlation between zonal wind stress-SST correlation. Negative correlation means that those models with stronger easterly winds have deeper thermoclines. (b) Correlation map (in contours) between zonal wind stress and thermocline depth index, calculated as the average between 5°S–5°N and 160°E–140°W. Areas of significant correlation at the 95% value are shaded. Colored shading highlight areas where correlation between the wind stress curl (Sverdrup transport) and the thermocline depth index is significant. Positive means northward Sverdrup mass transport. (c) Same as in Figure 3b but using z20 instead of the thermocline depth.

3.2. Equatorial Atlantic Thermocline

In the equatorial Atlantic, z20 is much deeper than the thermocline in the eastern part of the basin, both for CMIP5 models and reanalysis (Figure 4a), and its slope is much smaller than that of the thermocline. The annual cycle of the thermocline in CMIP5 is more similar to the reanalysis than that of z20 (Figure 4b). The z20 annual cycle is once again too weak, and almost flat in some models. Regarding its interannual variability, it explains, for some months, less than 30% of the thermocline depth variance (Figure SM3). While z20 is not significantly related to model SST in any point of the basin, the depth of the thermocline shows a moderate correlation in the east, where SST-z20 relationship is the weakest (Figure 4c). Consistently with previous findings in the Pacific, in the equatorial Atlantic the thermocline depth shows a much stronger local correlation with zonal wind than the one shown by z20 does (Figure 4d). We posit that these differences are due to z20 being much deeper than the thermocline, and thus less reactive to changes in surface temperatures and zonal winds in the equatorial region.

The off-equatorial anomalous wind stress pattern related to a deeper thermocline suggests an anomalous equatorward Sverdrup mass transport (Figures 4e and 4f), consistent with the results found for the equatorial Pacific. Regarding z20, the wind stress pattern shows very strong loads in the subtropics, indicating a strong

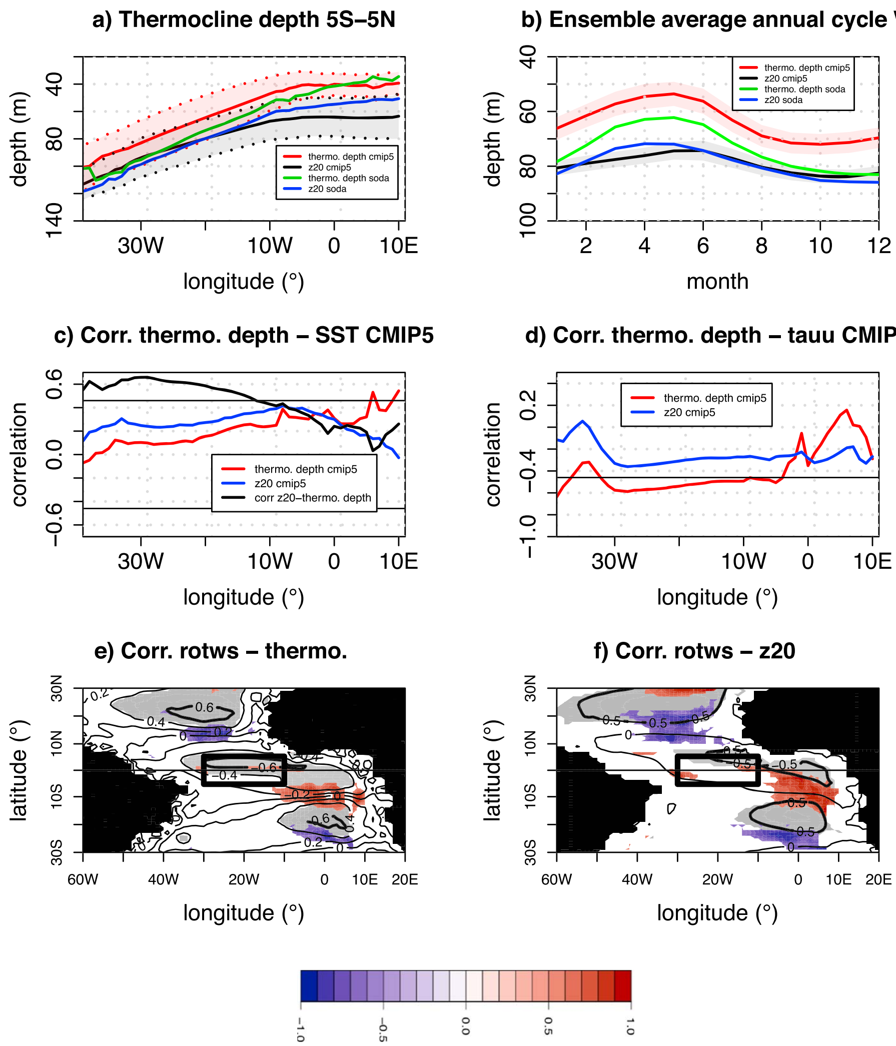

Figure 4. (a) Averaged (5°S–5°N) mean depth for the Atlantic basin of SODA thermocline (green), CMIP5-ensemble thermocline (red), SODA z20 (blue), and CMIP5-ensemble z20 (black). Dotted lines show intermodel spread (±1 SD). (b) Averaged (5°S–5°N) monthly mean depth for the central Atlantic basin of SODA thermocline (green), CMIP5 ensemble thermocline (red), SODA z20 (blue), and CMIP5 ensemble z20 (black). Colored area shows interannual variability for CMIP5 members. (c) Intermodel local correlation between thermocline depth and SST (red) and z20 and SST (blue) for CMIP5 models in the equatorial (5°S–5°N) Atlantic basin. Black line shows correlation between z20 and thermocline depth. (d) Intermodel local correlation between thermocline depth and zonal wind stress (red) and z20 and zonal wind stress (blue) for CMIP5 models in the equatorial (5°S–5°N) Atlantic basin. (e) Correlation map (in contours) between zonal wind stress and thermocline depth index, calculated as the average between 5°S–5°N and 30°W–10°W. Areas significant at the 95% value are shaded. Colored areas show the regions in which the correlation between the wind stress curl (Sverdrup transport) and the thermocline depth index is significant. (f) Same as in Figure 3b but for z20-zonal wind stress correlation.

influence of the subtropical anticyclones and very little impact of local equatorial zonal wind stress. The thermocline depth, however, is much more affected by local zonal winds and slightly less by the subtropical anticyclones.

4. Discussion and Conclusions

In the present work we address the use of z20 as an estimate of the thermocline depth in current state-of-the-art models. Although the reliability of z20 as a measure of the thermocline had been analyzed in observations (Fiedler, 2010), model reliability of this estimate had not been assessed so far, except for the work of Yang and Wang (2009) showed that using z20 in future climate projection could lead to errors. Here we show for the first time that such an estimate is also biased when used to explain the basic dynamics of the atmosphere–ocean interactions, showing a lack of connection in the western equatorial Pacific, especially due to the part mediated by the wind stress, and a spurious link between z20 and SST in the eastern equatorial Pacific. Regarding the eastern equatorial Pacific, our results further reinforce those from Li et al. (2015), who found that a too shallow thermocline in the eastern Pacific can be related with an excessive cold tongue in the central Pacific through ocean advection of colder waters. The even shallower thermocline in the east together with enhanced trades in the central Pacific (Li & Xie, 2014) provides a stronger upwelling and the development of a stronger cold tongue in models (Zheng et al., 2012).

In the central-west equatorial Pacific basin z20 is deeper than the thermocline so it is less affected by the surface winds (Richter, 2015), thus being less useful for understanding processes related to the action of the wind on the ocean surface. Our study shows that, even in the regions in which the climatology of z20 compares relatively well to the depth of the thermocline, the annual cycle is not well represented by this method. The z20 annual cycle is weaker than thermocline depths for the whole Pacific basin. This could have a great impact in variability and upwelling studies, for which a correct assessment of the depth of the thermocline is decisive (Richter, 2015). Moreover, the systematic error that z20 shows in the ensemble mean is smaller than that of some particular models. This calls for exercising great caution when using it in single model studies.

The difference in the eastern region of the Atlantic between z20 and the depth of the thermocline is even greater than in the Pacific Ocean. However, Voldoire et al. (2014) posited, for the CNRM model (included in our ensemble), that the thermocline (estimated as z20) is too shallow in the west and too deep in the east due to too weak easterlies. Again, the annual cycle of z20 is too weak in this region, and some models show very little interannual variability. This effect is especially evident in the Northern Hemisphere spring months, in which northwest African upwelling takes place, and could bear consequences on studies of that Atlantic feature. According to our results, the thermocline would be much shallower in the east and a bit shallower in the west when compared to the SODA thermocline, which makes the bias of the thermocline different from the z20 bias. This suggests that the problem might lie in the lack of response of z20 to zonal equatorial winds. This highlights the need for using the right definition of thermocline depth, in order to further narrow the origin of model errors in this region. A recent paper of Cabos et al. (2017) put forward the important role of the south subtropical anticyclone and heat advection in explaining equatorial biases. They use as diagnostic z23, which our results suggest—it being a representative isotherm—is heavily influenced by both the southern and northern subtropical anticyclones and more sensitive to equatorward Sverdrup transport than the physical thermocline (Figure SM4). Therefore, we should be cautious regarding the conclusions related to thermocline dynamics using this estimate.

The present work provides evidence suggesting that the thermocline reacts more clearly to equatorial zonal winds in the center of the basin, while z20 is more affected by other factors, such as the northern anticyclone in the Atlantic. Therefore, a correct definition of the thermocline depth is needed to avoid errors and incorrect conclusions in the assessment of model bias and variability and their ability to reproduce ocean–atmosphere interactions in the equatorial Pacific and Atlantic Oceans.

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